

Thermoelectric response of fractional quantized Hall and reentrant insulating states in the $N = 1$ Landau level

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(Received 15 November 2012; published 4 February 2013)

Detailed measurements of the longitudinal thermopower of two-dimensional electrons in the first excited Landau level are reported. Clear signatures of numerous fractional quantized Hall states, including those at $\nu = 5/2$ and $7/3$, are observed in the magnetic field and temperature dependence of the thermopower. An abrupt collapse of the thermopower is observed below about $T = 40$ mK at those filling factors where reentrant insulating electronic states have been observed in conventional resistive transport studies. The thermopower observed at $\nu = 5/2$ is discussed in the context of recent theories which incorporate non-Abelian quasiparticle exchange statistics.

DOI: [10.1103/PhysRevB.87.075302](https://doi.org/10.1103/PhysRevB.87.075302)

PACS number(s): 73.43.-f, 73.50.Lw, 72.20.Pa

I. INTRODUCTION

The thermoelectric power of low-dimensional conductors provides a view of such systems that is distinct from that offered by conventional charge transport. For example, it has been shown that in the disorder-free limit the longitudinal thermopower S_{xx} of a two-dimensional electron system (2DES) at high magnetic field is given by $S_{xx} = -S/(|e|N_e)$, where S is the system entropy, N_e the number of electrons in it, and e the electron charge.¹⁻³ The potential for access to such a basic equilibrium thermodynamic variable by means of a nonequilibrium thermal transport measurement is particularly enticing in strongly correlated low-dimensional systems where unusual electronic degrees of freedom often exist.

The strongly correlated electron system of interest here is a 2DES in which a perpendicular magnetic field B has positioned the Fermi level in the first excited ($N = 1$) orbital Landau level. It is well known that such a system displays a remarkably diverse array of unusual collective electronic phases. Conventional transport measurements on this system have established the existence of several fractional quantized Hall effect (FQHE) states, including the even-denominator state at Landau level filling fraction $\nu = nh/eB = 5/2$ (with n the electron density and h Planck's constant) and the odd-denominator states at $\nu = 7/3$ and $8/3$.⁴⁻⁶ In the highest-mobility samples intriguing insulating phases with *integer* Hall quantization have also been observed lying in between various FQHE liquid states.⁷ The situation is further enriched by the application of an in-plane magnetic field component.^{5,8-12} The in-plane field destroys the $\nu = 5/2$ FQHE and, initially at least, replaces it with an anisotropic compressible phase similar to those found in the $N \geq 2$ Landau levels.¹³⁻¹⁶

In this paper we report detailed measurements of S_{xx} in the $N = 1$ Landau level in a 2DES of extremely high quality. Our measurements extend down to about $T = 20$ mK, where the thermopower is strongly dominated by electron diffusion rather than phonon drag effects. In this regime clear signatures of almost all of the known FQHE states in the $N = 1$ Landau level are observed in S_{xx} . Below about $T = 40$ mK the above-mentioned insulating phases appear and abruptly quench the thermopower. In the vicinity of the $\nu = 5/2$ FQHE we find

S_{xx} to be in rough quantitative agreement with recent theories which incorporate the enhanced entropy expected from non-Abelian quasiparticle exchange statistics.

II. EXPERIMENTAL DETAILS

The sample used in this experiment is a modulation-doped GaAs/AlGaAs heterostructure grown by molecular-beam epitaxy (MBE) on a (001)-oriented GaAs substrate. The 2D electron gas resides in a 30 nm quantum well sandwiched between thick layers of $\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}$ and buried 210 nm below the sample top surface. After low-temperature illumination with red light, the 2DES has a density of $n = 2.9 \times 10^{11} \text{ cm}^{-2}$ and a low-temperature mobility of about $\mu = 3 \times 10^7 \text{ cm}^2/\text{Vs}$. A rectangular bar, 6 mm wide by 12 mm long, is cleaved from the parent wafer and then thinned, from the substrate side, to about 130 μm thickness. Chemical etching of the top surface confines the 2DES to two independent 3 mm² square mesas positioned along the bar. Six AuNiGe Ohmic contacts are placed at the corners and two side midpoints of each mesa. A thin film heater, of serpentine shape, is deposited at one end of the bar and covers most of the bar's width. Narrow evaporated Ti/Au contact lines run from each of the Ohmic contacts to the 2DES mesas and from the heater to a patch bay at the opposite end of the bar. This end of the bar is In soldered to the cold finger of a dilution refrigerator and serves to define thermal ground. The inset to Fig. 1 illustrates the sample layout.

As reported previously, the 2DES functions both as the thermoelectric material of interest and as an *in situ* thermometer.¹⁷ At magnetic fields close to strong integer quantized Hall states, the longitudinal resistivity ρ_{xx} of the 2DES provides a sensitive thermometer which is used to calibrate the phonon-dominated thermal conductances $K_{1,2}$ of the bar between each 2D mesa and thermal ground. We find that these conductances scale with temperature as $\sim T^{2.6}$ for $T \gtrsim 40$ mK and depend as expected on the distances between the 2DES mesas and the thermal ground.¹⁸ The phonon mean free path extracted from these conductance measurements is weakly temperature dependent but otherwise broadly consistent with nearly boundary-scattering-limited phonon transport.¹⁹ Although the conductance measurements

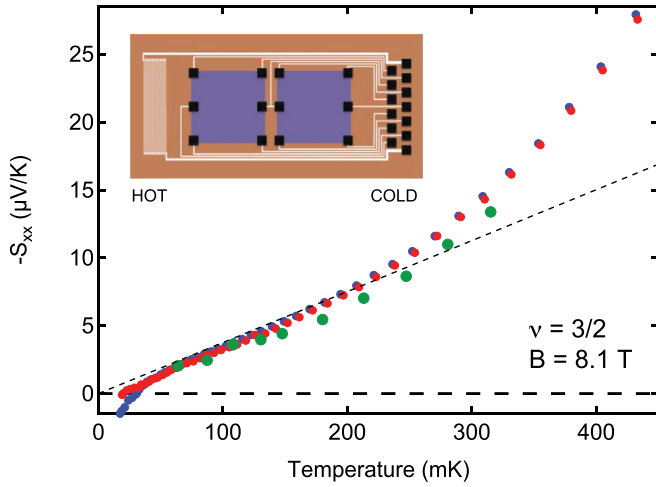


FIG. 1. (Color online) Thermopower vs. temperature at $\nu = 3/2$. Red and blue dots correspond to data from the two 2DES mesas on the sample bar. Green dots are from a previous measurement on a different sample.¹⁷ Inset shows device layout, with serpentine heater at the left and contact patch bay at right.

are made in the presence of a large magnetic field, we find no evidence for any systematic dependence upon the field. The conductances $K_{1,2}$ allow us to determine the temperature profile along the bar when a heat flux is applied.

In contrast to our previously reported quasi-dc thermopower measurements, which were hampered by long thermal relaxation times (~ 10 – 100 s) of the sample bar, we here report precision low-frequency ac results of much higher quality and at considerably lower temperatures. This is possible owing to the far shorter thermal relaxation time (< 1 ms) of our present device.²⁰ By applying an ac current (at typically $f = 13$ Hz) to the serpentine heater, a heat flux and temperature gradient along the bar are created at frequency $2f$. The induced longitudinal thermoelectric voltages in the 2DES are lock-in detected at $2f$. No frequency dependence or anomalous phase shifts of the thermoelectric voltages were observed at these low frequencies. Care was taken to ensure that the temperature drop ΔT across either 2DES mesa was always less than 10% of the mean temperature of the 2DES. Dividing the measured thermoelectric voltage by ΔT yields the longitudinal thermopower S_{xx} . We concentrate here on the thermopower data obtained from the 2DES mesa closest to the thermal ground; except in the few instances discussed below, essentially identical results were obtained from the second 2DES mesa.

III. RESULTS AND DISCUSSION

A. Ground Landau level

Before turning to the thermopower in the $N = 1$ Landau level (LL), we discuss our findings at filling fraction $\nu = 3/2$. Here the upper spin branch of the $N = 0$ LL is one-half filled and the 2DES is well approximated as a Fermi liquid of composite fermions in zero effective (orbital) magnetic field. As reported previously,^{17,21} at sufficiently low temperatures S_{xx} depends linearly on the temperature T . In this regime

phonon drag effects are negligible and the thermopower is dominated by diffusion within the 2DES. The situation resembles that at zero magnetic field where the standard Cutler-Mott theory of thermopower applies.²² Figure 1 shows our present high-precision S_{xx} data at $B = 8.1$ T where $\nu = 3/2$. A clear crossover from linear to superlinear temperature dependence is seen. In the superlinear regime above $T \sim 200$ mK phonon drag effects are likely becoming significant. However, the low Fermi temperature T_F of the composite fermion metal at this filling suggests that finite-temperature corrections to the Cutler-Mott result for the diffusion thermopower could also be involved. Following Cooper, Halperin, and Ruzin,² the linear temperature dependence of S_{xx} in the diffusive regime can be used to estimate the mass m_{CF} of the composite fermions at $\nu = 3/2$; we find $m_{CF} \approx 1.7m_e$, where m_e is the bare-electron mass.²³

For temperatures above about $T = 40$ mK the thermopower data extracted from the two independent 2DES mesas are virtually identical. Below this temperature, where S_{xx} is numerically small, the two data sets differ and individually begin to deviate from simple T -linear behavior. Indeed, the observed thermoelectric voltages can even change sign at very low T . This behavior may be analogous to universal conductance fluctuations (UCFs) in disordered mesoscopic conductors.^{24–26} In this low-temperature regime we find that the thermoelectric voltages can fluctuate aperiodically with magnetic field in the field regime around $\nu = 3/2$ and display strong sensitivity to the thermal history of the sample. Both of these signatures are familiar from UCF phenomenology. Above 40 mK these anomalies rapidly subside.

B. First excited Landau level

Figure 2(a) shows the measured longitudinal thermopower S_{xx} between filling factors $\nu = 2$ and 3; i.e., in the lower spin branch of the $N = 1$ Landau level, at $T = 200$ and 60 mK. These data vividly reveal thermoelectric signatures of fractional quantized Hall states at $\nu = 5/2, 7/3, 8/3, 11/5$, and $14/5$, with deep minima in S_{xx} at the appropriate magnetic fields developing as the temperature is reduced. This is, of course, the expected behavior for gapped quantized Hall states. We emphasize that the broad zeros of S_{xx} in the integer quantized Hall states at $\nu = 2$ and 3 are genuine; no spurious signals have been subtracted from these data. This demonstrates that extrinsic thermoelectric signals in our measurement circuit are negligible. In this temperature range we find S_{xx} to be remarkably quantitatively consistent from one cooldown of the sample to the next and to be essentially independent of which of the three possible contact pairs on each mesa is used to detect the thermovoltage. These observations contrast with ordinary electrical transport which often shows significant sensitivity to thermal cycling and choice of contacts. We speculate that this consistency reflects the connection of S_{xx} to the thermodynamic entropy of the 2DES rather than the details of charge transport through the system.

The temperature dependence of S_{xx} at $\nu = 5/2$ and $7/3$ is shown in Fig. 2(b). From about $T = 200$ mK down to roughly $T = 50$ mK S_{xx} is thermally activated ($S_{xx} \sim e^{-\Delta/2T}$) at both of these fillings. Energy gaps of $\Delta \approx 430$ mK, for both

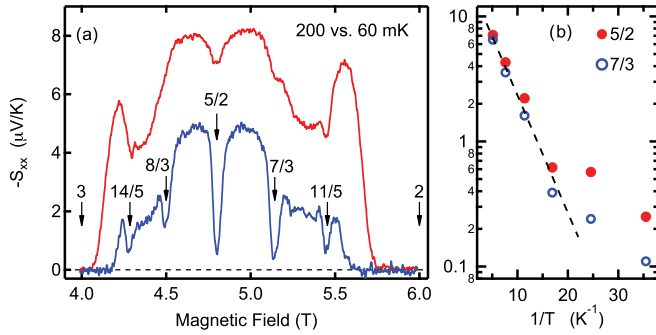


FIG. 2. (Color online) (a) S_{xx} between $\nu = 2$ and 3 at $T = 200$ (red) and 60 (blue) mK with various quantized Hall states indicated by arrows. (b) S_{xx} at $\nu = 5/2$ and $\nu = 7/3$ vs $1/T$. Dashed line corresponds to an energy gap of $\Delta = 430$ mK.

$\nu = 5/2$ and $7/3$, are estimated from the data. Statistically identical values are obtained from the two 2DES mesas. These gap values are consistent with prior determinations²⁷ based on measurements of the longitudinal resistivity ρ_{xx} . At lower temperature S_{xx} deviates from simple thermally activated behavior. Similar low-temperature deviations from thermal activation are commonplace in resistivity measurements in quantized Hall states and are often taken as evidence for hopping between localized electronic states. Alternatively, thermal decoupling of the electron system from the lattice cannot be unambiguously ruled out. However, this seems less likely here both because strong temperature dependences of S_{xx} are observed at other nearby magnetic fields (see below) and because S_{xx} is measured in the absence of any electrical current which causes Joule heating.

As the temperature is reduced below about $T = 40$ mK substantial qualitative changes are observed in the thermopower in the $N = 1$ Landau level. These changes are most dramatic at magnetic field locations between the prominent fractional quantized Hall effects at $\nu = 5/2$ and $7/3$ and between $\nu = 5/2$ and $8/3$. Figure 3(a) illustrates the change in S_{xx} which develops between $T = 41$ and 28 mK. In particular, around $B = 4.67$ and 4.93 T deep minima appear in S_{xx} . These minima develop quite suddenly as functions of temperature, with Fig. 3(b) showing the temperature dependence of S_{xx} at $B = 4.67$ T. Interestingly, as Fig. 3(b) shows, at temperatures just above the transition, the thermopower is roughly temperature independent. This is a strong deviation from the linear temperature dependence of S_{xx} in ordinary metals and in the compressible metallic phases of the 2DES at $\nu = 1/2$ and $3/2$ in the lowest Landau level.^{2,17,21}

We believe that these additional low-temperature minima in S_{xx} are associated with the reentrant integer quantized Hall effect (RIQHE) phases known to exist in the $N = 1$ Landau level.⁷ These states are insulating configurations of the 2D electrons in the $N = 1$ Landau level that appear between the major incompressible FQHE liquid phases at $\nu = 5/2, 7/3, 8/3, 11/5$, and $14/5$. Qualitatively similar to the so-called “bubble” phases which exist in the $N \geq 2$ Landau levels,^{28,29} the RIQHE phases in the $N = 1$ Landau level likely possess at least short-range crystalline order. Recent transport experiments have revealed that the collapse of the resistivity ρ_{xx} to zero and the formation of the integer quantized Hall

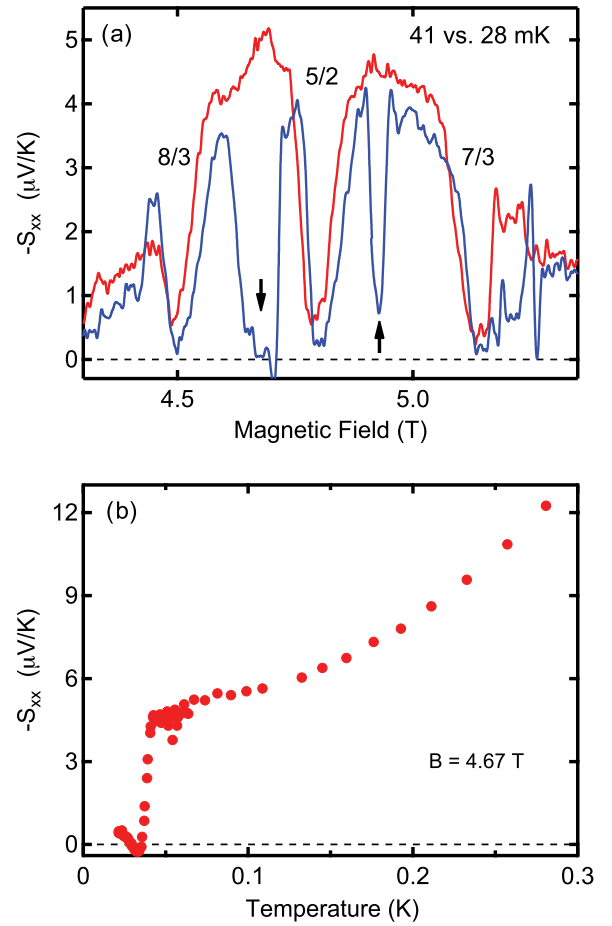


FIG. 3. (Color online) (a) S_{xx} between $\nu = 2$ and 3 at $T = 41$ (red) and 28 (blue) mK. Arrows indicate field locations where a particularly strong temperature dependence is observed. (b) S_{xx} vs T at $B = 4.67$ T.

plateau is remarkably abrupt as a function of temperature.³⁰ We find that these resistive transitions coincide with the collapse of S_{xx} that we are reporting here.

Similarly abrupt collapses of S_{xx} are seen at other RIQHE states in the $N = 1$ Landau level, including those adjacent to the $\nu = 7/2$ FQHE state in the upper spin branch of the Landau level. In some cases S_{xx} first shows a local maximum before falling toward zero as $T \rightarrow 0$. These thermopower results, coupled with recent resistivity measurements³⁰ and prior reports of magnetic field hysteresis and nonlinear transport signatures,⁷ strongly suggest that the RIQHE phase develops via finite-temperature first-order phase transitions within the 2DES. Interestingly, a significant change in the temperature dependence of S_{xx} has been previously observed to accompany the transition to an insulating phase of two-dimensional holes in the ground, i.e., $N = 0$, Landau level of a bilayer system.³¹

We note in passing that at the lowest temperatures ($T \sim 20$ mK) S_{xx} can change sign and become positive in narrow ranges of the magnetic field (the conventional sign of S_{xx} for electrons is negative). These sign changes are most obvious in the $N = 1$ Landau level near the RIQHE states, but are evident elsewhere as well (as Fig. 1 demonstrates at $\nu = 3/2$). Such sign changes are not surprising since S_{xx} depends essentially

on the derivative $\partial\sigma/\partial\mu$ of the conductivity with respect to chemical potential.^{22,32} In a mesoscopic sample universal conductance fluctuations produce a distinct “magnetofinger-print” and thus sign changes in S_{xx} versus magnetic field are certainly expected. In the RIQHE in the $N = 1$ Landau level, the dramatic nonmonotonicity of the Hall resistance ρ_{xy} (and hence Hall conductivity σ_{xy}) might also be expected to produce sign changes in S_{xx} via the generalized Mott formula first advanced by Jonson and Girvin.³² We emphasize that while these very-low-temperature anomalies are not identical in the two 2DES mesas and depend on the thermal history of the sample, they do not obscure the qualitative collapse of the thermopower associated with the onset of the RIQHE.

Finally, we return to $\nu = 5/2$ where recent theoretical work³³ has suggested that S_{xx} might reflect the anticipated non-Abelian exchange statistics of the quasiparticle excitations of the Moore-Read ground state.³⁴ Yang and Halperin³³ have predicted that owing to the ground-state degeneracy of an ensemble of non-Abelian quasiparticles, the thermopower S_{xx} near $\nu = 5/2$ will, in the clean limit, be temperature independent and proportional to $|B - B_0|$, the deviation of the magnetic field from its value B_0 at $\nu = 5/2$. Quantitatively, they find $S_{xx} = -(B - B_0)/B_0 (k_B/e^*) \ln d$, where k_B is Boltzmann’s constant, $e^* = e/4$ the quasiparticle charge, and $d = \sqrt{2}$ the quantum dimension appropriate to the Moore-Read state (or its particle-hole conjugate). This result is expected to be valid at temperatures low enough that other sources of entropy are frozen out but also high enough to smear the tunnel splittings between quasiparticles that will ultimately lift the ground-state degeneracy.

Figure 4 compares our low-temperature S_{xx} data near $\nu = 5/2$ with the theoretical prediction of Yang and Halperin.³³ While our data are quantitatively roughly consistent with the theory, they do not offer compelling support for it. At these low temperatures, the sub- $\mu\text{V/K}$ thermopower results in extremely small thermoelectric voltages ($\lesssim 2$ nV at $T = 20$ mK with $\Delta T = 2$ mK). Substantial signal averaging is thus required and renders the data sensitive to long-term drifts in the measurement setup. Indeed, as Fig. 4 shows, the location of the $\nu = 5/2$ minimum is not precisely the same at each temperature; small, history-dependent shifts of FQHE minima were frequently encountered. These difficulties prevented us from cleanly observing the expected

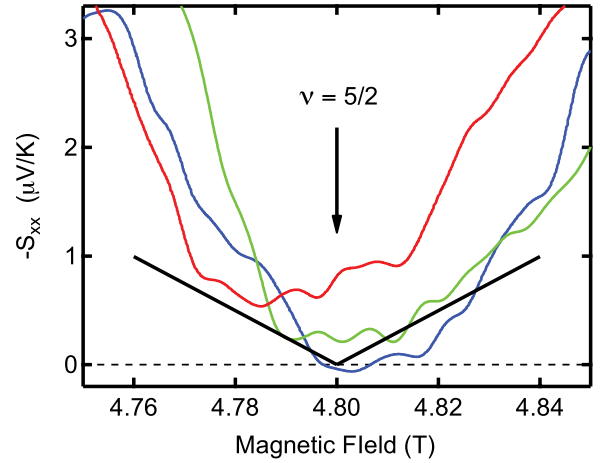


FIG. 4. (Color online) S_{xx} near $\nu = 5/2$ at $T = 20$ (blue), 28 (green), and 41 (red) mK. Solid black lines give the theoretical prediction of Yang and Halperin (Ref. 33).

temperature independence of S_{xx} on the flanks of the $\nu = 5/2$ minimum. Future experiments, possibly employing the recently suggested Corbino geometry,³⁵ may improve the situation.

IV. CONCLUSION

In conclusion, we have presented measurements of the diffusion thermopower of an ultrahigh-mobility two-dimensional electron system in the fractional quantum Hall regime at temperatures down to $T = 20$ mK. Our data clearly reveal thermoelectric signatures of several fractional quantized Hall states in the $N = 1$ Landau level. At $\nu = 5/2$ and $7/3$ the temperature dependence of the thermopower implies energy gaps of approximately $\Delta \approx 430$ mK for both states. More strikingly, we observe abrupt collapses of the thermopower coincident with the appearance of insulating RIQHE phases in both spin branches of the $N = 1$ Landau level.

ACKNOWLEDGMENTS

This work was supported via DOE Grant No. DE-FG03-99ER45766 and Microsoft Project Q.

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